Sensori-motor Learning in Movement-Sound Interactive Systems: a Review

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Contents

1 Introduction

The general idea of the LEGOS project is to fertilize interdisciplinary expertise in gesture-controlled sound systems with neurosciences, especially regarding sensori-motor learning. We believe that sensori-motor learning is not sufficiently considered for the development of interactive sound systems. A better understanding of the sensori-motor learning mechanisms involved in gesture-sound coupling should provide us with efficient methodologies for the evaluation and optimization of these interactive systems.

The project considers three perspectives:

- *Gesture learning or rehabilitation*: The task is to perform a gesture guided by an auditory feedback. The sensori-motor learning in this case is assessed in terms of the gesture precision and repeatability.
- *Movement-based sound control*: The task is to produce a given sound through the manipulation of a gestural interface, as in digital musical instruments. The sensori-motor learning is assessed in terms of sound production quality.
- *Interactive Sound Design*: The task is to manipulate an object or a tangible interface that is sonified. The sensori-motor learning in this case is assessed through the quality and understanding of the objet manipulation.

The literature on gesture-sound interactive system and sensori-motor learning is scattered in separate different research domains and communities, such as Sound and Music Computing, Neurosciences, Interactive Sound Design, Sonification, Rehabilitation, Sport Sciences.

The large majority of neuroscience papers on the human motor system deals with visual, haptic and vestibular sensory inputs and rarely mention the auditory modality. Historically most of papers that report on auditory-motor mechanisms concerned speech learning and production. On one hand, due to promising applications in movement learning (mostly in sport) and rehabilitation, there is an increasing number of studies showing the potential interest of auditory feedback. The technology used in these types of applications remains generally rudimentary. On the other hand, the most advance interactive gesture-sound systems are found in the music and computing field, but lack of systemic studies evaluating these systems. Moreover, no studies are reported on sensori-motor learning.

The aim of this document is to review the literature related to the use of gesture-sound interactive system linked to different applications, namely sonification for movement learning, motor rehabilitation with auditory feedback, digital musical instruments and sonic interaction design. The document starts with a short review of important concepts and definition related to sensorimotor control and feedback.

Due to the constantly increasing number of papers published in these area, we considered this document as a work in progress. This material will be used to feed a synthetic review paper.

2 Concepts and definitions

During a continuous interaction with a device for a gesture-sound task, the user is involved in a fast running loop. The physiological and functional characteristics of his biological sensors, his biological actuators and obviously of his nervous system determine the dynamics of the interaction. The quasi-instantaneity of the interaction in that loop let for the nervous system very few time to decide and react. Even if the interaction is voluntary and controlled, the nervous system does not have enough time to continuously involve some of its structures that are certainly important for the task (planification, aiming, decision making, problem resolution, reinforcement, etc...); such stuctures might act either at the beginning or the end of the task, or at a greater time scale. However, certain neural structures are known to be able to deal with such a fast interaction and to be able to process the associated sensory and motor signals. It is quite difficult to establish a clear distinction between structures and functions of the nervous system that are able or not to intervene during the interaction. Both levels are adaptive through the brain plasticity. Both levels can adapt through the brain plasticity. However the sensori-motor level uses a specific memory in order to learn new motor skills or new interactions : the procedural (or praxic) memory which has specific properties. It has been proposed (Schmidt, 1975) that this memory stores in particular motor programs corresponding to specific motor skills. Consequently, it is very common, in the field of neurosciences of movement, to introduce, as a theoretical tool, a separation between two levels of neural signal processing: the sensorimotor level and the cognitive levels. The following subsections present the main concepts used in our approach.

2.1 Sensorimotor and cognitive levels

As it was written above, a very common and useful distinction in Neurosciences has been made between two levels of neural activity in the nervous system. These two levels are respectively the *cognitive level and the* sensory-motor level (Paillard, 1985). Cognition is defined in (Kerlirzin et al., 2009) as the ensemble of mental processes including the capture, storage, transformation and use of experience and knowledge. These cognitive processes are largely voluntary and conscious. Perception, memorization, reasoning, information processing, problem resolution, decision making are part of these processes. The sensory-motor level refers to a more low-level set of processes linked to the transmission to the brain of signals coming from the sensory receptors, to the adjustment of muscle length and forces, and to the regulation of feedbacks loops involved in the control of movement. In the LEGOS project we will be particularly interested in the sensorimotor system and especially in the function and adaptive properties of sensorimotor loops, as defined in (Wolpert and Ghahramani, 2000).

2.2 Sensory feedback

Feedback, when making a movement, is defined in (Hartveld and Hegarty, 1996) as "information received back by the appropriate control centers in the brain on the resultant movement". This sensory information is provided during a task or after a task achievement and can be either intrinsic or extrinsic; this is depicted in figure 1. The notion of contingent feedback is also currently used in the study concerning learning.

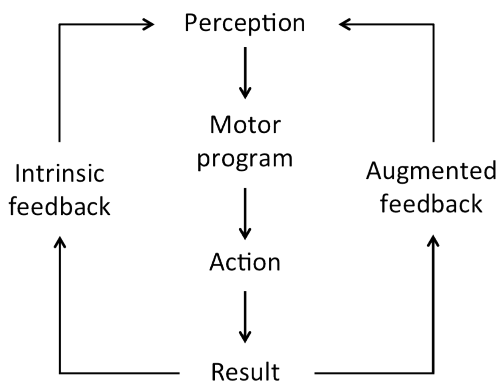

Figure 1: Schema of feedback received by the sensorimotor system when doing an action.

Intrinsic feedback - Any movement of the body generates intrinsic feedback which is a sensory (somatic) information resulting from the deformations of the sensory organs (receptors) during the movement itself. It can be for instance tactile, proprioceptive or kinesthetic.

Extrinsic feedback - Extrinsic feedback (also called augmented feedback) is information provided by an external source that can supplement the intrinsic feedback. It can be of any form (auditory, visual, verbal, generated by a specific equipment like computer, sensors giving biofeedback, ...) and can thus be conveyed by any sensory modality.

Contingent feedback - Contigency means that the feedback strongly corresponds with task behavior that can be controlled by the people involved in the interaction. For instance, the contingent feedback may concern velocity, effort, force etc... The contingent feedback can be provided either at the end of the task or during the task.

2.3 Augmented feedback

Two types of augmented feedback are generally delivered to the subject : knowledge of performance (named KP in the following) and knowledge of result (named KR).

Knowledge of performance - KP gives quantitative or qualitative information about how the movement is performed.

Knowledge of result - On the other hand, KR concerns the goal to achieve and tells about the subject's success (or failure) in achieving the task; the subject can use this information to perform better on the next attempt of his task. For example, in an object reaching task, KR could indicate whether the movement was correct or not, and KP would inform about movement quality related to the goal, such as "move your trunk less" (Subramanian et al., 2010).

Discrete and continuous feedbacks - Sensory feedback can be produced with either *discrete* events or *continuous* signals. It can also use iconic sensory signals (visual symbols or iconic sounds) or quantitative information (for instance continuous signals related to velocity, direction of movement, force etc...).

2.4 Auditory feedback

Auditory feedback consists in providing extrinsic feedback through the auditory modality, whether this signal carries KP or KR, continuous or discrete events. It can be delivered either as auditory icons, earcons, speech or sonification, even though it is non verbal most of the time. These different types of auditory feedback are described in The Sonification Handbook (Hermann et al., 2011). In the next chapter a large number of papers will be cited to illustrate the use of auditory feedback to convey information and enhance motor learning. Much research is needed in that domain and it seems to represent a growing interest among diverse scientific communities.

Advantages - Using the auditory channel to transmit extrinsic feedback offers many advantages. Zatorre (Zatorre et al., 2007) underlines the close relationship between auditory and motor systems in the temporal domain (example of tapping a beat with one's foot or fingers). This has implications in the study of motor control and learning in music. Physiologically speaking the ear is quite powerful to analyze and discriminate fine temporal events, particularly compared to vision. Robertson notes that (Robertson et al., 2009) hearing possesses a high rate response towards amplitude and frequency modulations. Furthermore processing time of auditory information is notably shorter than visual (Baram and Miller, 2007). This appears as an important property considering the rapidity of sensorimotor interactions and reactions to perturbations. On the other hand, vision allows our system to make previsions and to anticipate within our environment. Another advantage of audio is that it can be processed by our sensory system without interfering with normal visual or proprioceptive feedback processes ((Robertson et al., 2009)). In addition in sensory-impaired people the auditory modality in easily integrated with their remaining senses without disturbance. Dozza (Dozza et al., 2007) gives the example of vestibular losses.

Spatial information - Audition is also an efficient channel for giving spatial information or report self-body orientation and motion in space. It is in the meantime a modality that requires few cognitive effort to focus on (while keep looking at a screen for example). The use of 2D or 3D sound spatialization can be an interesting way to provide spatial information to the user. Spatialized sounds, if properly generated, are easily interpreted by the nervous system.

2.5 Perception-action

Cognitivist approach in perception-action - From a cognitive (cognitivist) point of view, when performing a motor action it is essential to constantly process data coming from our sensory system. Perception enables us to modify and correct a trajectory (either on a single limb or a global trajectory as while driving a car). The trajectory must be predicted, simulated internally and evaluated, to achieve the best performance. A typical example is given by (Kerlirzin et al., 2009) : a waiter when lifting a bottle from his tray will automatically adjust the force in his arm as the bottle leaves its surface. On the other hand, if the bottle is removed by anyone else, it is impossible for the waiter to anticipate and adapt. Even if he receives warning he will not keep the tray still.

Direct perception approach - A different approach, inspired by the ecological approach in psychology (Gibson, 1986), proposes that foundation for perception is ambient, ecologically available information. This theoretical approach assumes that the central nervous system (CNS) does not have to make calculus or computation in order to draw a link between sensations and actions. It only has to found in the environment the appropriate signals that have to be properly associate with the correct motor response.

Knoblich and Flash (Knoblich and Flach, 2001) investigated the links between perception (and self-perception) and action production ; mostly with visual modality. Experimental results tend to demonstrate the importance of self-perception to predict actions. They also mention that perception of other persons could help us predicting our action, but in to a lesser extent. Action observed are linked to imagined actions to predict forthcoming action effects.

Music performance- Auditory and motor systems are interacting strongly in music performance. In this context, the motor system must achieve high level performances about timing, sequencing and spatial organisation. Movement features of a musicians are inter-dependant on their own produced sounds and of external sounds (other musicians or playback track) ((Zatorre et al., 2007)) . Rhythm is a particular aspect of music (specific) in which auditory-motor interactions are extremely advanced (for example in percussion players or tap dancers). Tapping one's foot happens spontaneously on acoustic cues but not on visual cues, which might show that specific of auditory-motor interactions occur in the time domain. The presence of metrical structure in sounds proved to be enough to imply auditory-motor interaction.

Rythm - Tapping to the beat can be defined as a feedforward auditory-motor interaction: auditory information is predominant on motor output as prediction and expectations are made (Zatorre et al., 2007) . On the other hand feedback interaction allows continuous control of the sound, and enables musical expressivity. Zatorre reports an experiment in which auditory feedback was delayed and distorted, causing timing problems (for asynchronous feedback) and action selection but no timing change (for pitch alteration). This suggests perception and action rely on one unique mental representation. Zatorre reports that several brain regions are involved in timing and sequencing but notices the lack of study about spatial processing in musical tasks (Zatorre et al., 2007).

In (Conde et al., 2011) the authors used SRT (serial reaction time) tests to investigate the role of task-irrelevant auditory feedback during motor performance in musicians. SRT tests showed that feedback increased right hand performance but learning skills were unchanged. Hickok et al. (Hickok et al., 2003) investigated brain activity when listening to speech and music, and using functional MRI noticed areas involved in auditory-motor development for speech production and musical abilities.

2.6 Sensorimotor learning

Learning types - In (Franklin and Wolpert, 2011), Franklin and Wolpert detail three main types of learning in the field of sensorimotor control : supervised learning, reinforcement learning and unsupervised learning. Supervised learning is driven by the error between the target of the action and the action. This error is provided by an external agent named the supervisor. Reinforcement learning is driven by a positive or negative reward signals. Unsupervised learning is driven by signals not related to an error but by the experience of the task by the agent. Risks, rewards and costs (and not only error) are also involved in adaptation and could explain unusual gesture trajectories performed under specific circumstances such as sensory or motor perturbation (as can be seen in (Forma et al., 2011)) and (Kagerer and Contreras-Vidal, 2009) or (Davidson and Wolpert, 2004)).

Implicit an explicit learning - As decribed by Subramanian et al. (Subramanian et al., 2010), *explicit learning* is the attainment of accessible declarative knowledge of components of a motor action through cognitive process that can be tested by component recall or recognition. *Implicit learning* defines an unconscious mechanisms of learning that is involved in everyday skills and acquired through physical practice without the requirement of declarative instructions. Implicit learning is usually measured with serial reaction time task (SRTT) tests. During SRTT tests participants are asked to respond to a set of stimuli, each of them requiring a particular action. Transition probabilities between some stimuli are controlled and fasten thus participants learn the transition probabilities.

Adaptation Sensorimotor learning is obviously a time-related process in dynamical environment and actions. It has been proposed (Smith et al., 2006) that adaptation could be achieved with two learning processes, one faster and one slower. These processes learn and forget faster and slower, respectively. This mechanism allows quick assimilation and better long term stability to perturbation and during de-adaptation process. Note that other models describe a unique fast process and several slow processes (Lee and Schweighofer, 2009). Franklin and Wolpert give many examples and conclude by saying that learning is optimally performed by the sensorimotor control system to integrate not only nonlinearity, non-stationarity and delays but also noise and uncertainty. They recently proposed that the optimization of movement during the learning is guided by an optimization constraint : to minimize the uncertainties. In addition, Wolpert (Wolpert et al., 2011) wrote and extensive review and synthetic paper on sensorimotor learning and possible learning algorithm that could be used by the neural networks of the CNS (and particularly by the cerebellum).

Plasticity and consolidation - Brashers-Krug (Brashers-Krug et al., 1995) focused on plasticity and adaptation of the sensorimotor system. He studied de-adaptation and catastrophic interference during learning and suggests that motor learning can undergo a process of consolidation. On this subject see also (Davidson and Wolpert, 2004) who points out that learning can take a very long time (hundreds of gesture repetition) and de-adaptation is very often faster. Davidson experiments different scaling down processes during de-adaptation.

Changes in Performance does not implies learning : as van Vliet writes (van Vliet and Wulf, 2006) the effect of feedback on motor learning often mixes the result of performance and learning. In a movement trajectory task learning can be mistaken with simple adaptation which Maulucci defines (Maulucci and Eckhouse, 2001) adaptation denotes trajectory modification that takes place immediately after training i.e. at the end of the training session; learning denotes trajectory modification that takes place some time after training i.e. the retention and use of trajectory modification from one session to another. Studies rarely assess this point and are concern usually short term effects. Long term studies or retention time tests still have to be carried out. Engardt (Engardt, 1994) raises also the question establishing a deep motor scheme during learning versus motor performance that can be easily washed out.

Auditory-motor transformation - An important aspect when studying auditory-motor learning is to consider auditory-motor transformation, the way the motor system is given auditory information. Warren et al. (Warren et al., 2005) proposed a model of auditory-motor transformation based on audio templates with which input auditory information is compared. Auditory representations emanate from this comparison and are used to constrain motor responses.

Adaptation to visuo-motor perturbation or discordance - In studying visuo-motor perturbation can influence on auditory-motor representation, Kagerer (Kagerer and Contreras-Vidal, 2009) noticed that movement planning can benefits from previous visuo-motor transformation in the same limb movement. He suggests that new visuo-motor internal models developed after a perturbation can be used by the audio-motor system : "the internal model formed during exposure to the visuo-motor distortion is immediately available to auditory-motor networks. In other words, speaking on a modeling level, the transformation of the difference vector between the visual target and hand position into the desired hand/joint kinematics and dynamics is being used by the system when the task suddenly becomes auditory-motor in its nature".

Effect of Context Evaluation of performance and learning is also linked to the context: mechanisms and results is certainely different within a musical control context or motor rehabilitation of a stroke patients. The particular case of rehabilitation is described in section 4.

In the context of gesture control in music and music performance, the produced movements are closely related to the auditory system since each move produces or influences a related sound (often related to the physical parameters of the gesture). Within this relationship, it would be interesting to assess the characteristics of learning skills toward adaptation (see 2.5).

3 Sonification for Movement Learning

Sonification is defined as the general process of conveying and transmitting any type of non-speech data and information through the auditory modality. The resulting acoustic signal, translats data relations and magnitudes into perceivable acoustic dimensions. Many examples of systems, techniques and methods can be found in the Sonification Handbook by Hermann et al. (Hermann et al., 2011). For about the past ten years, a scientific community has built up around the use of sonification for various usage. In this section we present a wide range of applications of sonification for movement learning that has been published in the scientific community. Studies here describe motor learning of a specific task with extrinsic auditory feedback in healthy subjects. Papers come from various fields, from music technology, art or sport sciences. Several large review articles will be referred to, describing experimental results or methodology points. Few papers tend to generalize principles of auditory feedback design to enhance motor control and learning. Definitions and basic concepts are rarely established and consistent over the authors. A substantial number of result is nonetheless available. Some complementary results can be found in section 4 and 5.3.

Sonification allows for providing extrinsic information through the auditory channel. Icons and earcons have been widely studied, especially in the field of sound design (Hermann et al., 2011). Sonification, in a general way, allows for richer sound generation and more complex interactions throughout the auditory modality (discrete, direct, time-related, continuous, etc...). One of the essential questions that is debated in the domain is precisely how to set up the relationship linking the action to the feedback and the interaction, that is, which sound to use and how to use it.

3.1 Movement and skills acquisition

A recent review paper, Sigrist and colleagues (Sigrist et al., 2013) examined papers on multimodal and unimodal feedback with healthy subjects (rehabilitation patients are thought to use and benefit in a very different manner from augmented feedback for motor learning). This review focuses on classic motor learning theories and presents results relatively to those theories (such as the Guidance and the Specificity of learning hypothesis). First, the authors remind the large contribution to motor theories and feedback optimization for motor learning brought by visual and visuomotor studies. Numerous results are detailed about concurrent, frequent and terminal feedback, task complexity, retention and guidance effects or adaptive feedback (changing the feedback rate display or threshold in the case of bandwidth feedback). The notions of self-feedback, self-efficacy, self-estimation of error and motivations are also mentioned.

Many examples of auditory-augmented motor tasks are depicted, in various domains and especially in sports and skill acquisition. The example of sport shows that natural (causal) auditory information are used by performers to progress, such as in table tennis where the sound of the bouncing ball can provide high level information about its spinning movement. Furthermore, as previously mentioned in the present document, extra visual feedback may overload the cognitive process in tasks mainly based on visuomotor actions. Sigrist and colleagues depict auditory feedback in three categories : auditory alarms, sonification of movement variables and sonification of movement error for motor training. Auditory alarms are considered to be easy to interpret, but do not allow for a continuous representation of the movement and do not give information on possible correction to make. Sonifying movement variables seems more motivating for the participants according to the literature, but Sigrist and colleagues argue that non-experts could not benefit from the sonification as it does not indicate clearly the correct movement to acquire. Sonifying the movement error could solve this issue. The authors argue nonetheless that almost no study investigated sport training with error sonification, probably because it is almost impossible to determine a correct target (or reference) movement in any case. Simple strategies of movement variables sonification have been explored in the literature, but general studies about how to facilitate motor learning and evaluation of the design of such process are still missing. Error sonification proved to reduced movement error in various tasks, but the retention of such learning and the potential dependence of subjects to the additional feedback still need to be explored. Generally, auditory feedback proved to be beneficial in various case with a context-dependent approach, but the authors deplore that no study explored auditory feedback regarding motor learning theories.

Ronsse and colleagues (Ronsse et al., 2011) investigated the neural aspects of augmented feedback on a bimanual coordination task. In this very detailed paper, the results provide support to the Guidance hypothesis with auditory feedback, at a neural level (for the first time to our knowledge). Two groups of participants were trained to blindly rotate left and right wrists on a manipulandum with a 90°out-of-phase coordination nuder fMRI scan. One group received visual feedback of the coordination and the other received an auditory rhythmic feedback playing alternative pitches indicating the coordination rate. Both groups improved with training, slightly slower for the auditory group, but behavioral and fMRI results showed that the visual group became dependent on the feedback and presented neural signs of ongoing reliance. A promising result is the capacity of retention of the auditory group observed in this experiment. The training session were somehow long : 4 days in a row before the day of the post-test.

Although continuous sonification during a movement can be pleasant, motivating and informative, van Vliet (van Vliet and Wulf, 2006) suggests that presenting a movement-concurrent feedback can decrease performance once it is turned off. She points out that concurrent and instantaneous feedback can disrupt intrinsic error estimation on the movement and lead to dependency of the subject. A solution can be introducing a few seconds of delay before providing the feedback but this would prevent real-time interaction and sonification.

De Götzen (de Götzen et al., 2006) focused on Fitts' law to sonify gesture parameters. Fitts proposed (1954) a mathematical model of the motor system that allows to estimate time movement in a reaching task depending on the width and distance of the target. It is nowadays an ISO standard to evaluate pointing devices. In their experiment de Götzen and colleagues ask participants to perform tuning tasks on audio, visual and multimodal modalities, while receiving sinusoidal sound as audio feedback to evaluate Fitts' model. Auditory feedback on the movement seemed to help participants with difficult tasks when presented along with visual feedback. Accuracy was better but speed decreased with audio feedback. These findings can be related to musical control.

In an interesting review (van Vliet and Wulf, 2006) van Vliet states that "prescriptive" feedback is more efficient than "descriptive" feedback in healthy subjects for a motor task. It is better to to give errors information and suggestions how to correct motion rather than just giving information on the errors. She also gives several types of feedback and parameters that should be taken care of to increase their efficiency :

- timing : feedback-dependency of the learner must be avoided by reducing the rate of feedback during trials - 50% of trials with no feedback has shown better learning. There seem to be a compromise to find between summary feedback (about every trial in a set) and average feedback (averaged on the set of trials).
- allowing the subject to chose when to give him the feedback can be beneficial for learning.
- feedback can also be delivered only within a range of performance ("bandwidth feedback") or when the performance is outside the bandwidth ("quantitative feedback") although it seems less effective.

More recently Rosati (Rosati et al., 2012) and colleagues compared auditory task-related and error-related feedback in a tracking task. The aim of the task was a tracking exercise with a minimum-jerk trajectory. They confirmed that auditory feedback can improve performance in a tracking task (where vision is required to execute it) and found that it could help learning to adapt to a perturbation. They also found that task-related feedback improved performance during a complex and unpredictable tracking task and that, relatively to the auditory modality, a constant-length task can be executed better than a variable-length task. Unfortunately no control group was included in the protocol. The results seem to show that error-related feedback (sonification of the error) was not beneficial and even deteriorate adaptation to a visual perturbation.

In the framework of the closure gap and Tau theories (Rodger and Craig (Rodger and Craig, 2011)) investigated the synchronization of tapping (left to right finger and hand movements) to continuous, dynamic or discrete auditory beats. With discrete sounds the synchronization error was smaller but the variability was lower with continuous sounds. Continuous feedback also proved to give rise to more sinusoidal finger movements, indicating less jerky trajectories.

Thoret (Thoret, 2011; Thoret et al., 2012) studied drawings sonification to investigate relationships between gesture-produced sounds and gesture recognition. He focused on the speed of the gesture used as the input of the physically-based friction sound model. He noticed people were able to recognized gesture trajectories with the friction sound they produced / generated by the model.

Serafin (Serafin et al., 2011) created and tested a system of virtual walk on a plank thanks to shoe-mounted sensors that control a multichannel surround sound system. The sounds were generated with a physically based model which simulates the sound of walking on different materials. The subjects were blindfolded and ask to walk virtual plank. No significant results have been found, but it seemed that subjects succeeded more when receiving haptic feedback than auditory feedback. Combination of both feedback did not proved beneficial.

Vogt (Vogt et al., 2009) presented a movement sonification system as an auditory feedback device to improve perception of body movements. Real-time optical tracking is used as well as positive, negative, music or speech sounds as a way to "change the perception including the proprioception of the subject" in order to enhance the conscious aspects of his movements. Sonification and "positive" sounds helped participants on comprehension and motivation. It suggests that this type of interaction may improve concentration and attention when acquiring new skills.

Castiello and colleagues (Castiello et al., 2010) went beyond visual perception of hand movement by measuring the effect of sound cues on visually-guided movements. They showed that the presence of an auditory stimuli (recorded sounds of materials) that is congruent with the visual information available can modify participants end point movement to reach and grasp an object partially covered with the same material.

Among the almost endless technical possibilities for sonification, Effenberg (Effenberg, 2004) evokes the ecological approach of perception in kinesiology, where a close relationship between movements kinetics and sound can exist. He describes that many kinetics events are per se related to a sound produced ; the motor system uses these sounds as an important input parameter - this has been shown in sport (Takeuchi, 1993). This relationship could be applied to silent part of human gesture to bring more information about the movement. This paradigm is thought to be beneficial for motor control and motor learning according to him. He supports that functionality and origin of sound are necessary when using sonification to get extrinsic feedback. He also insists that spatio-temporal features have to be respected regarded movement sonification to activate multisensory response of the system.

An interesting work has been done by Dubus and Bresin (Dubus and Bresin, 2013) where they reviewed 179 papers that used sonification of physical quantities in order to analyze methods of mapping, physical dimensions used and to detect successful and unsuccessful strategies. The main finding they reveal is that sonification mappings are rarely properly evaluated in the literature. The majority of the studies reviewed used low-level and sample-based synthesis, which encourages us to go towards more complex sonification. As far as the mapping are concerned, a large number of papers described direct mappings representing simple kinetics magnitudes with pitch or loudness.

Finally, Van Vugt (van Vugt, 2013) examined motor learning with auditory feedback and particularly the learning of temporal structures of a movement. In a first part he showed that non-musicians could benefit from temporal information provided by an auditory feedback, and that they are sensitive to distortion of that temporal feedback. Then he shows that rehabilitation patients can also improve upper limb movements thanks to auditory temporal feedback (see section 4 for rehabilitation applications). As far as musicians are concerned (see section 2.5 for more details) Van Vugt surprisingly found, with a new analysis framework about systematic and non-systematic variability, that expert musicians have become independent of the auditory feedback.

3.2 Sport

Sonification techniques of arm's movements have also been applied in sport and exercise as in (Effenberg et al., 2011) where the authors developed a 4-channel real time sonification of indoor rowing system. The principle of the system is to associate sounds with motor perception in order to enhance motor learning and precision. Each channel was dedicated to a movement feature ; participants were novices. Two type of sounds were used, among them one was amplified natural sounds from the rowing machine. After observation of the movement with a video, they were asked to reproduce it with their own technique. Training period was three weeks long. Distance to the model's movement was computed with DTW (Dynamic Time Warping). Results suggest that the synthesized sounds feedback made more precise and faster movements. Along with previous results showing real-time sound feedback could improve motor control, so as for motor learning with this experiment. Rowing was also investigated by Wolf (Wolf et al., 2011) but sound coded the error during the movement execution, but subjects did not improve their motor-learning. The authors insist nevertheless on the importance of other than visual information channel to provide extrinsic feedback.

Karageorghis (Karageorghis and Terry, 1997) underlines the benefits of music when practicing sport or activities in healthy patients. A better synchronization of rhythmic activities and a better feeling about physical exercise has been noticed. No interaction is studied in these papers.

Interlimb coordination while juggling has been shown to be improved by movement-driven audio feedback (see (Zelic et al., 2011) and (Bovermann et al., 2007) that exploits the advantages of audio on sight). Wellner (Wellner and Zitzewitz, 2008) also found that the short processing time of auditory information could help participants in tasks where synchronization and speed are required (obstacle overcoming while walking on a treadmill with virtual reality). Sound was judged more helpful that visual cues in that case and improved gait speed. The authors underline the potential of task-specific feedback for rehabilitation in virtual environments. Note that subjects were asked to chose the sounds used and rated pleasantness, unambiguousness, and helpfulness of the sounds.

3.3 Sensorial subsitution

Auvray et al. ((Auvray et al., 2007)) tested the vOICE, an auditory-visual substitution system, and showed that auditory information could replace visual in locomotor guidance, localization, pointing and object recognition tasks. Participants indeed reported they were amused by their ability to use the system. Another example of visual to auditory conversion is the experiment carried out by Formal et al. (Forma et al., 2011) where the visual feedback of the patient's hand was converted into localized or head-related spatial sounds.

Our sensory system confirmed to be plastic to a certain extent and sonification may be helpful to sensory-impaired people. Both studies revealed that some task were more appropriate (or easier?) to auditoy-visual substitution ; different tasks may be more associated with one sensory modality or another.

4 Motor rehabilitation with auditory feedback

Motor rehabilitation is generally performed after a stroke that leads to typical physical pathologies like hemiparesis (motor and sensory impairment or paralysis of limbs), apraxia (loss of know-how with objects), aphasia (inability to talk) or hemianopsia (loss of half of the visual field). The goal of motor rehabilitation is to restore ability of being independent towards activities of daily living (ADLs). This is essential for the patients to re-integrate into social and domestic life (Avanzini et al., 2009). In this chapter we will focus on studies and methods investigating audio extrinsic feedback in rehabilitation therapy processes and see the rationale to use it. Avanzini studied the use of the different form of mutlimodal feedback for robot-assisted rehabilitation in the literature. The main results of this review suggest that only 40% of reviewed studies (total number of 36) used audio feedback and that only a few used complete sonification (described as the mapping of multidimensional datasets into an acoustic domain).

After the acute phase of the stroke (from t0 to t+3 months) where intensive care are lavished, recovery continues in the sub-acute (t+3 to t+6 months) and chronic phases (after t+6 months). It is noticeable that major recovery of upper limb extremity occurs in the early months ((Maulucci and Eckhouse, 2001)), and that many studies advice to start rehabilitation soon and intensively after stroke. However Maulucci also suggested that a specific rehabilitation on a motor function should be done (on order to be accurately tested) after 6 months once patients have reached a plateau in their recovery, to ensure improvements are not due to early spontaneous recovery. Van Vliet (van Vliet and Wulf, 2006) suggests indeed we adapt the parameters of feedback depending on the stage of rehabilitation of the patients. Indeed, Cirstea (Cirstea et al., 2006) precises stroke severity and possible cognitive impairments must be taken into account when setting up rehabilitation process.

4.1 Augmented feedback for rehabilitation

During rehabilitation physiotherapists always use augmented feedback in movement therapy ((Hartveld and Hegarty, 1996)). Three main ways to deliver it during rehabilitation are specified in this review : personally (verbal or non-verbal), through equipment to enhance intrinsic feedback (accessories, tools) and equipment to give artificial feedback (mainly electronic devices).

Feedback can sometimes also be related to the benefits of the task or a form of reward. The three modalities of feedback were compared : the first one revealed weak and slow, the second improved the functional realism of the task, and the last proved accurate, immediate and quantitative. Hartveld (Hartveld and Hegarty, 1996) conclude by giving parameters necessary for efficient augmented feedback during rehabilitation : has to be rewarding, desirable, plentiful, related to kinematics and kinetics of the movements, functionally related and precise.

Using extrinsic feedback to help rehabilitation is mainly motivated by the great plasticity of the nervous system that can be beneficial to stroke survivors ((Subramanian et al., 2010)). "Adaptive plasticity linked to rehabilitation is predicated on the hypothesis that short duration connections achieved through fast Hebbian learning facilitate the establishment of more durable connections occurring with repeated practice".

A useful review is presented in (Subramanian et al., 2010) concerning post-stroke upper limb motor learning aided with extrinsic feedback. Although only one study detailed used auditory feedback this systematic review concludes that evidence can be found that extrinsic feedback is beneficial for motor learning in post-stroke rehabilitation. They explain that, in rehabilitation, knowledge of performance (KP) is used predominantly. A frequent provision of knowledge of results (KR) can however improve performance but disturb long term memorisation of a task (see also (Engardt, 1994)).

Implication of the subject and motivation are important to patients to focus on the rehabilitation exercise. In (Avanzini et al., 2011) Avanzini states that finding the strategies to enhance engagement and motivation in motor rehabilitation is an open research challenge. We can therefore wonder whether sound and/or music can be an interesting modality.

4.2 Motivations

In (Karageorghis and Terry, 1997) Karageorghis explains that exercises are facilitated by synchronization with musical accompaniment. Music can also reduce the feeling of effort during exercise. Finally, the great variety of styles and atmosphere offer by music can, if chosen well, enhance enjoyments levels and adherence to physical activity, says Karageorghis. However it is still unknown how this mechanism can work in motor rehabilitation (i.e. with impaired and often shell-shocked patients). Beyond motivational aspect that music can obviously offer during exercise, several group experiments on the use of auditory feedback to provide patients with either KR or KR.

It is generally recognized that feedback should have a multimodal form to be more effective (Avanzini et al., 2011) Multimodal feedback can improve the performance in a complex motor task but the potential of auditory feedback is still underestimated. Avanzini also proposes that auditory feedback for rehabilitation in ADLs should be used along with other modalities, and particularly to sonify the user's movements and the environment.

One of the strongest advantages of auditory feedback is that it is easily perceivable without requiring much attention or strong cognitive effort (Avanzini et al., 2011). Furthermore for patients that lay in bed for a long period of time and suffer from lack of attention, auditory feedback is a practical way of augmented feedback.

Many questions still remain unanswered and some authors like van Vliet (van Vliet and Wulf, 2006) deplore that most of the existing research on the subject only evaluate the effectiveness of devices and do not try to answer more fundamentals (or theoretical) questions about KP vs KR effects or feedback integration mechanisms.

Few studies observed temporal parameters of feedback (frequency, summary, average, delay,...) in stroke patients and none with audio feedback.

Observing and understanding the mechanisms involved in auditory-motor learning on healthy subjects is an essential milestone towards comprehensive understanding in patients who were subjected to a stroke. Nevertheless, stroke patients may suffer from sensory lesions or lack of concentration compared to healthy subjects ; the transposition of models and experiments from healthy to stroke patients will have to be lead carefully. Thus, it is not clear whether patients recovering from stroke can learn with the same processes as healthy subjects? Their intrinsic feedback paths may be damaged giving even more importance to a provision of extrinsic feedback. As processing of implicit vs explicit feedback can be changed, and difficulty of one task will differ from healthy patients, changing parameters of the feedback will have different effects on patients (van Vliet and Wulf, 2006).

In the next section we report on specific experimental studies that indeed applied auditory feedback in a rehabilitation process. Protocols and sounds used are quickly described and major results are presented.

4.3 Upper limb movement

Hemiparesis (impairment or paralysis of a whole right or left side of the body) is a major cause of disability after a stroke. Upper limb dysfunctions impair most of the ADLs and cause a loss of independence therefore can lead to social exclusion. Upper limb rehabilitation appears then as a major issue in rehabilitation after a stroke.

A frequent type of test concerns reaching gesture with upper limb. Most of the rehabilitation processes include this procedure which is fundamental for recovery of ADLs. One of the first study that used auditory feedback in rehabilitation of upper limb was published by Eckhouse (Eckhouse et al., 1990) in 1990. Hemiparetic subjects received KR in the form of tones indicating subject's score and precision in a reaching task of a target presented on a touchscreen. The test group had better performances than the control group due to augmented sensory feedback. Eckhouse concludes that enhancing recovery of stroke patients with specific and regulated feedback on guided limb motion is proved. This relies upon the plasticity of the central nervous system. He adds "the realization of significant modification demands utilization of specific feedback presented to sensory systems capable of participating in the restorative process", underlining the importance of the design of the feedback and understanding of the mechanisms involved.

(Maulucci and Eckhouse, 2001), tested real-time sonification to give auditory feedback during a reaching task with hemiparetic patients. The task consisted in touching targets situated in front of the subjects. They were given the deviation from the normal path they were following with their hand and the magnitude of this error through frequency and amplitude modulated sounds. This spatial sonification (with a magnetic hand-tracking device) was found to help "visualize" the path by the subject. The authors also noticed that some subjects were lured by the final target and less focused on the path to follow ; this raise the question of simultaneous KP and KR needs and designing correctly the appropriate sound feedback. To ensure the training is the most adapted to ADLs the authors propose that an other task should be added at the end of the gestural path (such as pressing a button); the whole reaching strategy may thus be modified. In addition, the authors detailed many gesture kinetics and kinematics parameters they recorded to evaluate movement and learning in such a reaching test.

Robertson and colleagues ((Robertson et al., 2009)) recently carried out an study on reaching movements with auditory feedback on hemiparesis patients, comparing the brain hemisphere affected and two types of auditory feedback (volume and balance). Their main conclusions state that the effectiveness of the auditory feedback depends on the hemisphere affected by the stroke and no significant difference was found between amplitude and balance feedback. Patients with the left hemisphere damage even showed worse results with the feedback. One hypothesis is that lesions in the left hemisphere may have disrupt feedback processing capacity. The authors also suggest that auditory feedback would be more appropriate for giving temporal information and KR rather than KP (better for visual feedback).

In (Kagerer and Contreras-Vidal, 2009), Kagerer and colleagues compared visual and auditory feedback in a reaching task on a graphic tablet. In the auditory condition blinded participants had to move a cursor toward sound sources emitting beeps arranged around the control monitor. This task was actually tested versus a visual equivalent (see details in the article), and Kagerer adds that "at no stage of the experiment the auditory-motor relationship itself was manipulated". Results suggest that participants were able to locate pretty well the azimuth of the sound source, and showed a cross-modal aftereffect but no significant benefits of auditory feedback has been demonstrated.

Recently, Forma and Hanneton (Forma, 2010) conducted an experiment with a similar protocol to observe motor-learning and aftereffect with presence of auditory-feedback. The task consisted in reaching a center-out virtual target presented on a screen by moving a cursor on a graphic tablet (subjects could not see their hand). The sound was modulated as in (Robertson et al., 2009) in amplitude and balance indicating the subjects distance from the target and relative position. Among the 128 trials to go, in 80 of them a perturbation was introduced that rotated the visual feedback of the cursor. The test group received visual feedback only, the second group received sound feedback through headphones. Preliminary results showed that curved trajectories are observable during perturbation and aftereffect in both groups as Kagerer noticed. In (Kagerer and Contreras-Vidal, 2009) the authors noted that audio-guided hand trajectories remained straight during visuo-motor adaptation ; this may be a lead to others investigation.

Ghez and colleagues (Ghez et al., 2000) explored musical scales for movement sonification to improve inter limb coordination in patients suffering from proprioception deficits. They showed encouraging results using sonification of joint motion and timing cues, but without control experiment.

4.4 Rhythm

Whitall (Whitall et al., 2000) gives the two main advantages of the bilateral rhythmic auditory cueing system (BATRAC). First, evidence suggest that motor learning could be enhanced with bilateral movements (simultaneous or alternating) : both arms are linked in one control unit in the brain and experiments showed that learning a task with one arm can lead to a transfer of skill to the other arm. Second, this protocol uses a rhythmic repetition that is a classic learning principle. We will also see later that the rhythm of sound or music can be a positive asset on rehabilitation. Whitall points out two important features among others of the rhythmic aspect of auditory cueing. A constant frequency leads to repetition of the same movement and the motor system can acquire a certain regularity ((Thaut et al., 1996)). Also, synchronizing the end of a gesture with a discrete sound give an attentional goal to the patient during the exercise.

4.5 Gait and posture

In (Dozza et al., 2007), Dozza precises that auditory and vestibular information are transmitted to the brain through the same nerve. It is likely that postural alignment is subconsciously influenced by auditory information : this stands as a rationale for using auditory feedback in balance rehabilitation. Another motivation can be found in (Easton et al., 1998) where the authors showed that sound delivered with two lateral speakers can reduce center-of-pressure sway in congenitally blind and sighted people.

The oldest studies available concern gait rehabilitation through auditory rhythmic cues and stimulation. On of the first advantages of auditory feedback proved thus to be the rhythmic aspect available to facilitate gait and cadence rehabilitation ((Thaut et al., 1996), (Thaut et al., 1997)).

In (van Vliet and Wulf, 2006) (and many more) the authors noted that auditory feedback improves performance in sit-to-stand (greater symmetry in body-weight distribution). An experimental study corroborates this point. In (Batavia et al., 1997), the authors report an augmented auditory feedback device with a pressure sensor in a stroke patient's wheelchair cushion. A buzzer sounds when the weight "is not properly distributed". The goal was to make the patient sit correctly on his wheelchair and stay straight. After 2 to 3 days the authors report an improvement in the patient's symmetry in weight and midline perception. After 7 weeks the patient was reported to sit alone and improved some dynamical controls of his trunk head and shoulders. The authors conclude that along with spontaneous recovery and physical therapy, auditory feedback proved useful. This case concerned only an isolated 74-year-old patient.

Engardt (Engardt, 1994) carried a study to assess long term effects of auditory feedback on sit-to-stand body weight distribution in patients with a paretic leg. It is noticeable that it is the only study we found which studied long term retention effects of auditory feedback in rehabilitation. Patient underwent the same body weight distribution in rising and sitting tasks 33 months after a 6 weeks training period with audio feedback (plus a control group). The results showed that patients in the feedback group had lost their relearned tasks performance after this time (more than the control group). However they were faster to accomplish them. Engardt proposed several hypotheses such as patients mostly used their healthy leg for speed and security after the tests. She concludes saying that an auditory feedback should be delivered with reduced frequency, in very long sessions (maybe thousand times according to Bach-y-Rita and Baillet (Bach-y Rita and Baillet, 1987)) over long periods of time and during open task situation (as the closed situations seemed not similar enough to a real environment for the patients).

Baram and colleagues (Baram and Miller, 2007) tried to evaluate the residual short-term effect of auditory feedback during gait rehabilitation. Fourteen multiple-sclerosis patients with gait disturbance mainly due to cerebellar ataxia participated. The authors tested mainly the effect of rewarding and support, as the auditory feedback was designed so that “a steady balance gait will produce a pleasant auditory cue, synchronized with the patient’s own steps, rewarding the patient for making the effort”. Their results suggest that the auditory feedback can improve walking parameters, all the more that the patient’s baseline speed was low. The feedback may sometimes have negative effect on healthy patients like disturbance. Nevertheless, the authors underlined that the inner mechanism between auditory signals and coordinating movements remained to be found and that large groups studies were required.

This study shows that auditory cues can be beneficial in gait rehabilitation and supports a previous paper about auditory-rhythm cues. Mcintosh (Mcintosh et al., 1997), used a rhythmic auditory stimulation (RAS) on Parkinson’s patients, first by matching their own baseline cadence and then increasing the rate of the cues (10%). Retention was also later tested without the device. The results suggested that velocity, stride length and cadence can be improved with increasing-rate RAS.

The studies reviewed in those papers tend to show the potential of auditory feedback on gait and posture rehabilitation, whether it is delivered from weight distribution or external cues and rhythmic stimulation. As a result we should keep in mind the beneficial effects of timing and rhythm of sound and music for rehabilitation (see Skill Acquisition below). Others auditory feedback systems for gait and posture rehabilitation use “bio-feedback” as they sense physical property of the body.

4.6 Bio-feedback

Bio-feedback can be defined here as the use of instrumented devices to provide physiological information of the movement. It consists most of the time in measuring data on the user's body during a specific task with the help of sensors and electronic devices (EEG, EMG, body kinetics, ECG, NFB, fMRI,...). The data is then transmitted back to the user as an extrinsic information through any modality. When the modality used is auditory, bio-feedback is a type on sonification of body physiological data (cf 2.c. Sonification).

Originally, audio bio-feedback was studied along with visual feedback and used very simple alarm-type sounds ((Dozza et al., 2007)). Bio-feedback has been mainly used for gait and posture tests often (in children with cerebral palsy) but the audio modality is still under-studied.

In (Batavia et al., 2001) the authors tested on a single patient (12,5-year-old) a membrane switch buzzer to study gait and equilibrium (the latter was tested with visual feedback). The authors underline the ability of the patient to walk on her own after 3,5 week of training with auditory feedback but this study focuses on a particular case.

In (Dozza et al., 2007) the authors tested the influence of an audio bio-feedback system on postural sway in healthy and with vestibular loss patients. A continuous low-volume sound was emitted and modulated when the subjects were swaying outside their natural range (previously measured). The sounds used were pitch and amplitude-modulated stereo sine waves. The physical parameters used for this mapping were sway in the media-lateral plane (balance and volume) and in the anterior-posterior plane (pitch) on a force plate. Procedure tested the sway eyes closed, then eyes opened with foam under their feet or not. The conclusion is that the subjects used the extrinsic feedback all the more as (proportionally) their sensory information was reduced. Variability of weight given to the different sensory information was also noticed.

Another study which can be described as auditory bio-feedback (Basta et al., 2008) tested auditory feedback on sway with isolated otolith disorders patients (who have been found to respond weakly to regular vestibular rehabilitation strategies). Thirteen subjects received no feedback and thirteen others received audio from the Sway-StarTM system that produces a single tone in 3 exercises : standing eyes closed and standing on foam eyes opened then eyes closed. The system is attached to the patient lower trunk and senses trunk angle velocity in roll and pitch planes. A tone was emitted when the angles crossed a threshold ; the tone was emitted from one (out of the four) loudspeaker towards the patients had to move to correct their sway. The exercises were performed everyday during two weeks. 85% of patients on the test group showed significant decrease of trunk sway, most significantly when walking on the foam. These results, even though quite sparse in the literature, show the positive effects of sound feedback through bio-feedback devices for rehabilitation. The lack of theoretical and computational analysis and models with auditory input is ubiquitous and much work has yet to be done to assess experimental procedures.

4.7 Robot-assisted rehabilitation with auditory feedback

A sizeable part of the studies carried on with auditory feedback concerned technology-assisted systems ; as technology progresses, this part is still growing. Unfortunately the actual benefits of the feedback on motor-learning are poorly assessed in that case. Their main advantage is that motion can be easily captured and augmented feedback is pretty easy to integrate as a servomechanism is already running. Robot-assisted rehabilitation is quite common in rehabilitation centers but expensive and unwieldy. It is generally used with augmented feedback, but not often with audio. Loureiro et al (Loureiro et al., 2003) has proposed an application where motor rehabilitation is controlled by both visual and haptic feedback.

Sound is often used as a reward to present KR and to improve the user's engagement in technology-assisted rehabilitation systems, as in (Cameirao et al., 2007). The patients is rewarded with a "positive sound" whenever he succeeds in a specific game.

Discrete auditory feedback in stroke rehabilitation using robotic manipulation is also presented by Colombo (Colombo et al., 2005) where the device provided visual and auditory feedback to the patient to signal the start, the resting phase, and the end conditions of the exercise (no details on sounds used).

Other work in rehabilitation using robot assistant was done by Secoli (Secoli et al., 2011). They showed that a simple sound feedback (beeps with frequency increasing with the tracking error) enabled the participants to simultaneously perform a tracking task and a distractor task effectively. They thus underline the potential of real-time auditory feedback of performance errors in robot-assisted rehabilitation systems. Accuracy is then computed as difference of position with and without the visual distractor.

Encouraging result have been also found by Rosati (Rosati et al., 2011).

Added to a regular task (tracking a target with loaded manipulandum arm), auditory feedback had no or little effect. But, in the presence of a distracting task sound feedback was helpful to increase performance without degrading the performance in the distracting task. Authors find nevertheless that auditory feedback should be more used in robotic therapy systems and is mostly limited only to background music or signifying task completion.

In a review (Avanzini et al., 2009) Avanzini investigated 47 papers describing 36 robot-assisted rehabilitation systems. He focuses on whether audio modality was used and what type of audio : earcons, auditory icons, speech and sonification. The first conclusion is that a majority of system do not use audio at all. Most of the time, auditory icons and earcons are used and the author underlines that only a few systems use sonification, showing that the potential of auditory feedback is still underestimated.

Finally, Avanzini (Avanzini et al., 2011) deplores that few cases of technology-aided rehabilitation have been transferred to real-world application in a medical context.

4.8 Virtual environments for rehabilitation

A derivative of robot-assisted systems is the use of virtual reality or immersive environments - also allowed by the development of real time aspect of gesture-sound interactive systems.

For reviews on rehabilitation in virtual reality context, see articles by Sveistrup (Sveistrup, 2004) and Holden (Holden, 2005). Only a few articles referenced deal with sound / auditory cues (see (Shing et al., 2003)). One system called MEDIATE uses multi-sensory interactive environment to enhance engagement in children in autism. The system can recognize features from the children (movements, voice) and adjust and transform the virtual environment in response. Interaction is predominant but this does not directly concern motor rehabilitation.

Most of the time, audio is used in this context to enhance spatial dimensions, such as orientation and localization ((Holden, 2005)). Multiple loudspeakers systems are often used to create “spatial” rendering and sensory immersive environment. Audio processing in virtual reality systems answer efficiently to a need for realism of these systems. Some virtual reality-based hand rehabilitation system with localization and spatialization do not concern rehabilitation (ex Cave system in (Cruz-Neira et al., 1992)).

Lehrer and colleagues (Lehrer et al., 2011a) and (Lehrer et al., 2011b) more recently wrote a large interesting article ton conceptualize multimodal interactive upper limb rehabilitation and to give systematic guidelines to design such systems. They focus on adaptive and interactive rehabilitation by the mean of phenomenological approaches and embodied knowledge brought into rehabilitation methods. The system they present is based on motion capture and can be adapted to particular rehabilitation needs through multimodal feedback (sound and video animations). Another application of rehabilitation using game metaphor is provided by Grasielle (Grasielle et al., 2007) that present a virtual reality platform for musical game. This relies on engagement and motivation enhancement with multi-sensory platforms.

Cameirao (Cameirao et al., 2007) set up a direct interaction virtual reality system where audio has a rewarding function. Stroke patients with left hemiparesis were tested with a hand motion tracking camera in a gaming environment, called Rehabilitation Game System RGS. Each time the patient (with or without paresis) accomplishes the goal of a specific game, a “positive sound” is triggered. No details are provided by the authors on the sounds used but it is only simple rewarding KR. The system is based on the hypothesis that “motor execution combined with visual feedback can trigger the mirror neuron system and thus give access to the central motor system.

Forma et al. (Forma et al., 2011) set up a reaching task system (magnetic hand tracking) where a continuous real-time sound feedback indicated the relative position (or distance) to a virtual sound-emitting target. The particularity of this experiment stands in during one protocol the feedback was presented as the “ears” of the participants were on the tracked hand. In this case, where the effector (the hand) and the sensor (the virtual ears) are spatially coincident precision was slightly better (less jerk, and more direct trajectories). This experiment shows that virtual environment can enable us to explore auditory-motor coupling and perception.

Note that continuous auditory feedback can also be used for realism but it is not directly related to movement but the object to which the feedback is associated, see Johnson (Johnson et al., 2003), Boian (Boian et al., 2003) and Nef (Nef et al., 2007).

Many papers conclude - as often - with the statement that further studies are necessary to investigate deeper the mechanisms of learning with auditory feedback in rehabilitation and evaluate its benefits. Most of the studies barely use the great potential of this type of feedback they tend to underline. Groups of patients are rather small and short term effects tested.

4.9 Comparative summary

A comparative summary of rehabilitation experiments using augmented auditory feedback is presented in figure 2.

Authors	Pathology/ Rehabilitation	Device	Audio	Movement modulation	Information	Diffusion
Maulucci et al. 2001	Stroke/Arm	Polhemus motion capture system	Sine	Frequency Amplitude	Hand position vs ideal reaching path	Computer
Basta et al. 2008	Otholith disorders	Accelerometer	Sine	Amplitude	Center of gravity position	4 LS
Dozza et al. 2005	Bilateral vestibular disorder	Accelerometer	Sine	Amplitude, Pan	Center of gravity position	4 LS
Huang et al. 2005	Stroke/Arm	Motion capture	Music	Scrolling speed ; additional sounds	Hand position	Headphones
Robertson et al. 2009	Stroke/Arm	Polhemus motion capture system	“Flying bee”	Amplitude, simulated binaural (ILD, ITD)	Hand vs target position	Headphones
Kagerer et al. 2009	None	Graphic tablet	Tones	None	Target position	2 front piezzo buzzers
Batavia et al. 2001	Spina bifida (walk disorder)	Pressure sensor	Complex	None	Heel on the floor	Integrated SwayStar speaker
Baram et al. 2007	Multiple Sclerosis	Accelerometer	“Beep”	None	Step	Integrated speaker
Mergner et al. 2003	Pakinson’s	Pressure sensor	Music	None	Toes adjustment + rhythm to follow	LS
Whitall et al. 2000	Stroke/Arm	BATRAC	Metronome	None	Cues	LS
Eckhouse et al. 1990	Stroke/Arm and hand	Touchscreen and touchplate	Tones and speech	None	KR (score)	TV sound system
Forma et al. 2010	None	Graphic tablet	Sine	Pan, amplitude	Hand vs target position	Headphones
Batavia et al. 1997	Stroke/sitting straight	Pressure sensor	Buzzer	None	Trunk angle	Buzzer
Basta et al. 2008	Parkinson’s	Heel, toe, metatarsals pressure sensors	Metronome	None	Gait cadence, velocity and symetry	LS
Dozza et al. 2007	Vestibular loss	Accelerometer	Sine	Pitch, amplitude	Postural sway in 2 directions	Headphones
Ferney et al. 2004	Gait/walk	Pressure sensor			Foot load	
Petrofsky 2001	Gait	EMG	Bio-FB			

Figure 2: Comparative summary (non exhaustive) of rehabilitation experiments with augmented auditory feedback.

5 Digital Musical Instruments (DMI)

The research field concerned by musical interfaces, Digital Musical Instruments and musical interactivity has significantly grown since 2000. In particular, several new approaches “beyond the keyboard” and MIDI representations (Miranda and Wanderley, 2006) have been proposed. The international conference NIME (New Interfaces for Musical Expression), started in 2001 as a workshop of the CHI conference (Bevilacqua et al., 2013), contributed to expand an interdisciplinary community composed of scientists, technologists and artists. A competition of new musical instruments also exists since 2009 held at Georgia Tech[1].

As illustrated in Figure 5, a Digital Musical Instrument (DMI) can be formalized as composed of an *interface or gestural controller unit* and a *sound production unit* (Wanderley and Depalle, 2004; Miranda and Wanderley, 2006). These two components can be designed independently, in contrast to acoustic instruments. This representation must be completed by the *mapping procedure* that allows to link the digital data stream, between the gesture data to the data input of the sound processor, often represented as a dataflow chart.

In (Wanderley and Orio, 2002), the authors postulate that input devices for musical expression are respecting two main trends: designing controllers that best fit existing motor control ability (e.g. imitating existing instruments) or designing so-called “alternate controllers” involving new gestural vocabulary (from a performance perspective). In all cases, different types of feedback mechanisms occurs as illustrated in Figure 5 the the primary feedback (visual, auditory and tactile-kinesthetic) and secondary feedback (targeted sound produced by the instrument). These feedback create action-perception loops that are central in the interaction.

In the field of musicology, acoustic and music technology, there have been an effort to formalize musical gestures (see (Godøy and Leman, 2009) for a review and in particular the review on sensorimotor control of sound-producing gestures (Gibet, 2009)). The filed of neurosciences has also integrated an increasing number of studies on music and performance (see for example the four special issues of the Annals of the New York Academy of Sciences: The Neurosciences and Music (2003, 2006, 2009, 2012) that covers a large spectrum of this research). Nevertheless, to our knowledge no study addresses directly sensorimotor learning in Digital Musical Systems. This is mainly due to highly idiosyncratic use of digital musical instruments, and the lack of repertoire and notation as found with acoustic instruments.

Most of the research work on Digital Musical Instruments concerns essentially the design issues in building digital musical instruments, i.e. designing the gestural controller, mapping, sound production unit and the interaction

[1]Margaret Guthman Musical Instrument Competition http://guthman.gatech.edu/

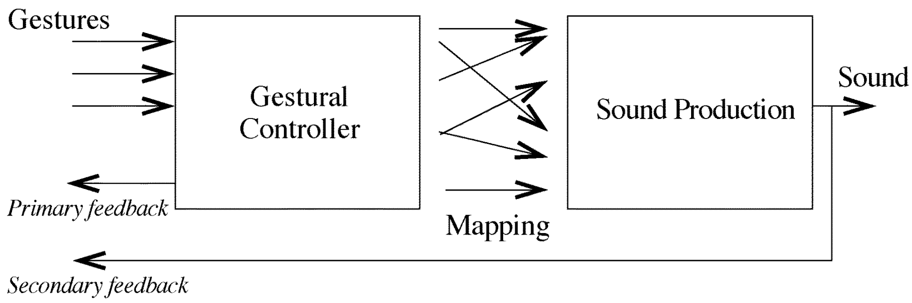

Figure 3: Symbolic representation of a Digital Musical Instrument (from (Wanderley and Depalle, 2004))

(Wanderley and Battier, 2000; Miranda and Wanderley, 2006; Paine, 2009; Paine, 2010). We report below works on the evaluation of Digital Musical Instrument and the few works of auditory feedback that have been implemented in augmented instruments for educational purposes.

5.1 Evaluating digital music instrument (DMI)

Wanderley et al. note that the design of input devices is generally associated to artistic projects with idiosyncratic choices, and generally lack of a general evaluation methodology. The authors propose to use tools from the Human Computer Interaction field (HCI), and define musical tasks that could be evaluated.

Also inspired by the HCI field, Malloch et al. (Malloch et al., 2006a) developed a design space for digital musical instruments. The design space is inspired by Rasmussen's theory of design (ecological interface design and SRK theory (Rasmussen, 1983)) and links Skill-, Rule-, Knowledge-based interactions to signal-, sign- and symbol-based interaction, respectively, for controlling music. Unfortunately, the authors do not propose evaluation methodology coherent with the proposed design space.

In (O'Modhrain, 2011) the author proposed an extended framework for DMI evaluation. They argue that Human Computer Interaction methodology is not sufficient since DMI are often evaluating based on their behavior during performances.The paper integrates different types of evaluation according to the perspective form the performer, the audience, the designer and the manufacturer (see table 1, p. 38 of (O'Modhrain, 2011)).

Different qualitative methods of evaluation have been reported. Hsu et al. (Hsu and Sosnick, 2009) assess the qualitative experience of musical systems by musicians and audience. Geiger et al. (Geiger et al., 2008) presented a study on participatory design of Theremin-like musical interface. They conducted an evaluation based on the AttrakDiff questionnaire for evaluating the hedonic and pragmatic quality of interactive products. Poepel in (Poepel, 2005) evaluates three digital string-based instruments together with a mapping. A questionnaire (five point Likert-scale) is filled by both professional and amateur musicians.

As already mentioned, quantitative evaluation of DMI, or of some elements constituting a DMI, require the definition of **musical tasks**. The principal tasks that have been reported in the literature are the following: pitch modulation, pitch selection, pitch selection and modulation, navigation, triggering (drumming), production of a sound target. We detail them below.

Pitch selection and/or modulation

Wanderley et al. (Wanderley et al., 2000) compare Round FSR, Linear FSR and Stylus Angle in a pitch selection and modulation task. The authors found that the users better prefer the round FSR than the others chosen transducer devices.

In the same way, Marshall et al. (Marshall and Wanderley, 2006) tested the following input devices for the same tasks: FSR, Accelerometers, Linear Pot (fader), Rotary Pot, Linear Position Sensor (Ribbon), Bend sensor. The authors found that the users better prefer the linear position sensor for pitch modulation, pitch selection and both. The FSR had also good results in a pitch selection task and the fader obtains good result in a pitch selection and modulation task. A complementary study by the same authors (Marshall et al., 2009) showed that comparing video camera, FSR, and accelerometers for a pitch modulation task reveals that FSR (pressing and rolling) is preferred by the participants.

A last study by Geiger et al. (Geiger et al., 2008) investigates the pitch selection by musical sequence making in a theremin configuration testing three different input devices: theremin, "glove theremin" and the Wii (with Wii joystick). The users gave an overall better rating to the Wii. The accuracy was also slightly better with the wii but not significantly.

Navigation

In (Vertegaal and Eaglestone, 1996), the authors compare between three input devices, mouse; joystick; and a glove, for navigation task in a timbre space. A repeated measure design was used with a group of 15 paid subjects who were asked to reach for target positions in the Sustaining instrument space using the various device types (FM synthesis). Usability of the device affects the efficacy of the system and low-dimensional device provides better performance. Efficacy is established by measuring the movement time needed to reach the 4D target position within a certain accuracy (where accuracy is overall Euclidean distance to target in 4D space). Movement time and accuracy was found best with the mouse. A better control integration is achieved with Power gloves (in x,y plane): it is more natural to move diagonally across the degrees of freedom of the input device. Integration thus does not refer to a learning process.

Triggering

Kiefer et al. (Kiefer et al., 2008) tested the usability of the Wiimote controller (compared to a Roland HPD-15 HandSonic[2]) for musical expression (based on guidelines by Wanderely et al. in (Wanderley and Orio, 2002)). The task is triggering (drumming along metronome). No significant differences for triggering is found. Interestingly they found that the Wiimote controller for triggering is hard to use because of a lack of physical feedback.

Another study for the specific task of triggering was performed by Collicut et al. (Collicutt et al., 2009). They compared V-Drum, Buchla Lightning II, Miramax Radio Baton, Tom Drum. The authors evaluate the performance with quantitative assessment of timing accuracy. They found that the Buchla Lightning II, next to the tom drum, the LII was the least variable of the 3 other instruments, which was unexpected due to the lack of playing surface with the LII.

Recently, Holland et al. (Holland et al., 2010) assess the use of haptic feedback in drumming learning and demonstrate that beginning drummers are able to learn intricate drum patterns from haptic stimuli alone.

Playing a sound target

Hunt et al. in (Hunt and Kirk, 2000) present a task-based evaluation: the goal is to reproduce a target sound with three interface-mapping couplings. The accuracy of the synthesized sound according to the target sound is evaluated by two experts (included the author). It results that the mouse was the best for the three groups of sounds (from non-complex to complex, many-to-many mapping).

The authors also assess the learning process of the interface–mapping coupling. This will be detailed in Section 5.2.

Gelineck et al. (Gelineck and Serafin, 2009) compare knobs and sliders in the task of reproducing reference sound samples (synthesized with physical model of flute and friction). An evaluation on Likert-scale is performed by the author and an impartial expert. The authors found that no significant difference exists between knobs and sliders.

5.2 Evaluating Mapping

The mapping procedures have been formalized and recognized as a key element in the digital instrument design, with both technical and artistic problematics (Hunt and Kirk, 2000; Hunt et al., 2003). In particular, several studies, methods, and tools have been published (Wanderley and Battier, 2000; Wanderley, 2002; Kvifte and Jensenius, 2006; Malloch et al., 2006b;

[2] http://www.skysun.co.za/musical_instruments/images/HPD-15.jpg

Malloch et al., 2007). We will present below works related to the evaluation of the mapping procedure.

Hunt and Kirk (Hunt and Kirk, 2000) inspect the learning process in a *longitudinal study* (three subjects over ten sessions). This study is then reused in (Hunt et al., 2000) comparing with system proposed in (Rovan et al., 1997). They found that more complex interface–mapping is preferred along the training process. The simple mapping allows for a rapid adaptation. Nevertheless, complex mappings are more satisfying once they have been mastered because they allow for more control and expressivity.

Merrill et al. (Merrill and Paradiso, 2005) evaluate between self-configured or fixed mapping with a given interface. Evaluation is essentially based on analysis of user experience (questionnaire). Stowell et al. (Stowell et al., 2009) use either discourse analysis or turing test method for mapping evaluation. Finally, Collins et al. (Collins, 2011) explore the evaluation "on stage" based on feedback by the performer.

5.3 Auditory feedback and sonification for instrument practice

A small number of works have been conducted on interactive systems giving auditory feedback during instrument practice, based on either sound analysis, MIDI data or movement analysis. Ferguson reported different interactive sonification algorithms to provide auditory feedback to singers and instrumentalists. The sonification is based on the real-time analysis of the sound (note onset, rhythm, loudness control, legato, and vibrato) and provide the player with knowledge of results (Ferguson, 2006). In the context of the iMeastro project (EU-IST), Larkin et al (Larkin et al., 2008) and Rasamimanana et al (Rasamimanana et al., 2008) implemented different approaches of auditory feedback for string players.Grosshauser and Herman also proposed different systems to provide multimodal feedback to violin playing (Grosshauser and Hermann, 2009). Hadjakos developed sonification feedback for piano players. His PhD work also contains a review of existing systems providing visual of auditory feedback for pedagogical applications (see Table 3.1, page 43 in (Hadjakos, 2011)). Promising results were obtained but no lare-scale evaluation have been conducted to assess these systems on the sensori-motor learning.

5.4 Summary

While there have been a large amount of research on musical interfaces and instruments, there is sill a few works the evaluation. There are very few quantitative analysis (e.g. 2 papers used quantitative analysis over 9 in case of gesture acquisition devices evaluation). Moreover, it seems difficult to generalize any published results that are very context dependent. Importantly, the learnability and in particular sensori-motor learning is totally absent.

6 Sonic Interaction Design

6.1 History: from sound quality to sound design

6.1.1 Evolution towards the sound control of industrial products

In Europe, during the second part of the 20th century, the industry has taken into account the sound in its product, especially in the automotive context ; important work was done to improve the body structure of the cars in order to reduce squeak and rattle sounds. Those efforts were even used by the industry for advertising : "Yet their search of silence continues - at the special Fisher Body sound laboratory", LIFE Magazine, in 1953. In the late 80s, significant efforts were devoted to noise reduction using active noise reduction. Until that period, the idea was to develop silent products like silent vacuum cleaner from MIELE company or silent automobile, reducing the sonic annoyance for the user. In the 90s, new expectations have occurred: the sound component provides a useful information about the state, the quality and the identity of an industrial object as well as its visual characteristics. Past slogans are giving way to new slogans: "Every sound has a meaning" (Citroën). The new field of research in sound quality was conceived mainly in the paradigm of psychoacoustics. A crucial aspect for the research in sound quality was to determine the relevant auditory attributes related to the preference of a sound product. During the last decade, the multidimensional scaling technique (MDS) has been successfully applied to different kinds of sound products to reveal their relevant auditory attributes for interior car sounds, air-conditioning noises, car door closing sounds, and car horn sounds (see (Susini et al., 2012a), for review). However, sound quality approach is usually considered as a post process to improve the sound of an existing product. Conversely, a sound design approach is implemented in order to create a "new" sound with the intention that it will be heard in a given context of use.

6.1.2 Sound Design: articulation between function and form

The Sound Perception and Design team, at Ircam, titles their website section dedicated to sound design[3] "Sound design: making an intention audible". This definition implies that a designed sound is new and constructed, and represents something other than the sound itself. This can be an object, a concept, a system or an action. There are two "intentions" that need to be audible: form and function. A designed sound needs to have a form

[3] see http://pds.ircam.fr/895.html

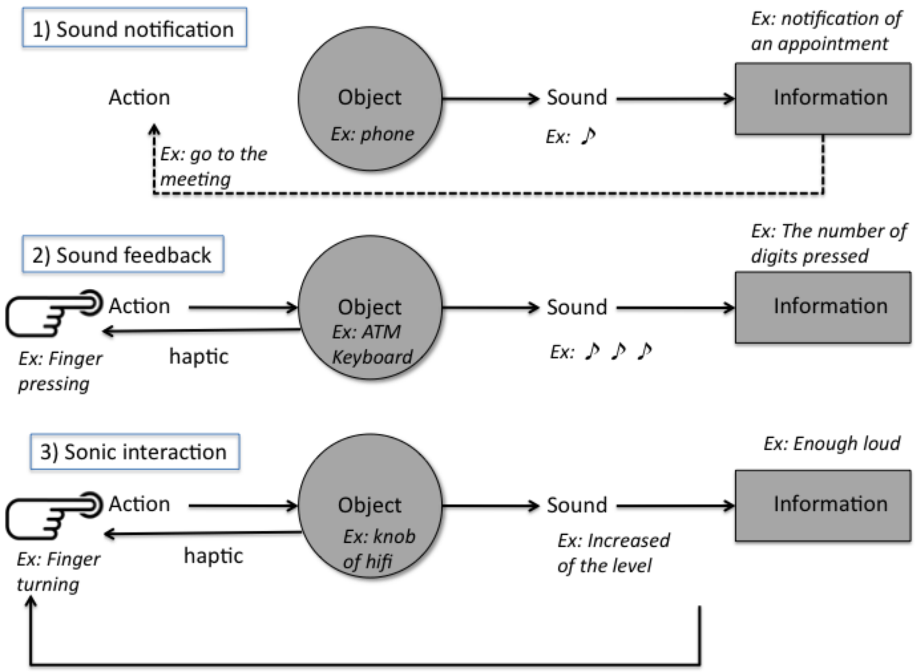

Figure 4: The three levels of complexity: sound notification, sound feedback and sonic interaction.

that is "appropriate" for the object/concept/system/action it represents, and it needs to fulfill a function, to communicate information about the object/concept/system/action to the individual. This information needs to be clearly heard and correctly interpreted for the design to be considered successful (Susini, 2011). It is the perceived information that gives a meaning to the sound.

6.2 From sound notification to sonic interaction

The function, defined in the previous section, can be considered as a relation between the sound and the action of the individual perceiving the sound with three levels of complexity, from sound notification to sonic interaction see Figure 4.

6.2.1 Sound Notification

Sound notification is used to prevent (to notify) an external event. An alarm sound is the perfect example of a notification; it provides an information about an urgency or a warning to the individual. The sound beacon is another example. It is the most simple type of function: the sound provides an information of a specific situation but there is no relation between the sound and the "eventual" reaction of the individual. Several studies have been done in order to define acoustically and perceptively the parameters of an alarm sound to convey different level of urgency or to reveal the type of problem. A first influential study (Edworthy et al., 1991) showed that some pulse and burst parameters had clear and consistent effects on the perceived urgency of a warning sound. Specifically, subjective judgments indicated that the faster the rate, the higher the pitch, and that the more randomly irregular the frequencies of the harmonics, the greater the perceived urgency. Those studies were applied specifically in the realm of aviation and automotive.

6.2.2 Sound Feedback

Sound feedback is used to confirm an action performed by a user. It could be a positive feedback, when the action is correctly performed, otherwise it will be a negative feedback. It corresponds to a knowledge of result (KR) of an object/concept/system/action: the type of sound feedback, positive or negative, provided after the performed action depends on the state of the system or the exactitude of the action. The validation of a transportation pass on a control terminal is a good example. In that case, there is a relation between the sound and the state of the system; the type of sound provided depends on the validity of the pass. Feedback sounds are typically used in the realm of human-computer interface; they are more often used as an illustration of an action such as in the Sonic Finder proposed by Gaver (Gaver, 1989), or in the sonified Event Os by VIPS. To make the relationship between sound and function of an interface more explicit, it has been proposed to take advantage of sound analogies with the physical world by the use of iconic sounds (Gaver, 1989). The most famous example is the sound of "crumpling" associated with the destruction of a "paper file". A sound interface called "the Sonic Finder" have been developed. The different associations are based on the concept of a metaphor corresponding to a causal representation of the event in a different context. Thus the sound feedback product is the result of the action taken in the physical world that makes sense, by analogy, in a virtual context. In the spirit of the Sonic Finder, VIPS[4] proposed a sound interface called "Event OS" for computer desktop using analogical relations with the sound world of the user. They prototyped a real-time interactive sonification for an operating system. For example when the mouse reaches the limit of the screen, a feedback is given by a sound of hitting glass. Another example is the "ile deleted" sound when dragging and releasing a file icon onto the trashcan icon with the metaphor of friction sound. The sound is produced by physical sound modeling with the SDT toolkit (Delle Monache et al., 2009).

[4] https://www.youtube.com/vipsunivr

6.2.3 Sonic Interaction

A sonic interaction is a continuous sound feedback: it is a sonic information on the best way for performing a task while performing that task. It corresponds to a knowledge of performance (KP) of an object/concept/system/action: the characteristics of the sound are directly related to any variation of the action performed by the individual or of the state of the system; for example, the sound produced by a musical instrument is directly dependent on the excitation mode.

Nowdays, the sonic component coupled to an action becomes an attractive feature for the conception of new objects/systems, in order to strengthen the physical reality and the performance with new artifacts, which is the case of the control handle Wii (Nintendo). The technological possibilities offered by the combination of physical modeling sound synthesis in real time - even if they are still limited to certain types of events (impact, friction ...) - and miniaturized embedded systems including sensors and micro-controllers - for example, the Arduino system - enable the design of interactive systems relevant to explore the perception of sounds of everyday objects in an interactive process. We speak here of interactive devices that will be discussed in the next section.

6.3 Interactive sound design and object

Sonic Interaction Design is a promising field that "emerged from the desire to challenge these prevalent design approaches by considering sound as an active medium that can enable novel phenomenological and social experiences with and through interactive technology" p.1 (Franinović and Serafin, 2013). The idea is to think about the design of sonic feedback, especially continuous interaction, for human computer interfaces HCI or digitally augmented devices. Interactive Sound Design, or Sonic Interaction Design as it is named in the network of reference European COST Action SID IC0601[5] is focused on the relationship between a user and a system in an active and dynamic point of view.

We present here a set of interactive objects integrating a sound dynamic component whose function is to allow control of a gesture to improve performance, promote learning and strengthen the emotional dimension of an object a priori silent. These objects have been developed for experimental setups (design and/or artistic) but also as devices designed to study the impact of a continuous sound feedback considering these different aspects: performance, learning, emotional and aesthetic dimensions.

Concrete objects differ from HCI during the action: concrete objects are handled directly by the fact of a physical action, the HCI are generally handled on screen via a mouse or directly in the case of touch screens.

[5] http://sid.soundobject.org

For HCI, there is a physical separation between sound and gesture. The sound is not the result of a physical production induced by a gesture. In contrast, the new based interactive devices allow direct control interface using sound feedback to inform the listener on gestures made. The objects are instrumented with sensors and micro-controllers for controlling a real-time sound synthesis tool in relation to the manipulation of the object. The objective is to establish a dynamic interaction between a user and the object, using the sound dimension. The manipulation of the object produces sounds, which in turn influence the handling of the object. We proceed in the same way with the everyday objects: a musical instrument is a good example of such an interaction. This is called audio interaction. The sound is vector of interaction, which is the function of the sound.

6.3.1 Examples of device

Shoogle Shoogle (Williamson et al., 2007) is a new way of interacting with a mobile device through sound by shaking, tiling or wobbling it. With these explicit actions, different scenarios have been proposed. The first one is called "eyes-free message box". The content of the SMS inbox is transformed into virtual sounding balls. When the user shakes the mobile device, long message are associated with metallic sounding balls and short messages with glassy sounding objects. Another scenario used the analogical relation with the keys in a pocket, when a long message arrived, the motion produces a sound like heavy iron keys contrary to shorter one like small coins. The liquid metaphor is also used in the case of the "liquid battery life" scenario. When the user shakes the device, to obtain an idea of the battery fullness, a liquid metaphor is used.

The Sonified Moka The moka pot is a stove top coffee which produced coffee by passing hot water pressurized by water steam through ground coffee, invented by the famous Italian firm Bialetti. The moka pot is composed of a bottom chamber containing water, a basket containing ground coffee, the filter and a collecting chamber. In order to prepare a coffee, you need to fill the bottom chamber with water, fill the filter with ground coffee and put together the three parts (the bottom chamber, the filter and the collecting chamber) by screwing the bottom and the collecting chambers. During a workshop organized by (Rocchesso et al., 2009), students have sonified the screwing action in order to provide the right degree of tightness using the metaphor of a violin player. The moka was instrumented with a force sensor between the filter and the gasket. The sound of an elasto-plastic friction model (SDT toolkit) is related to the force signal of the sensor. The timbre quality changes dynamically with the tightness of the screwing. When the tightness is to low, the feedback sounds like a glass harmonic and is transformed gradually to a rubber sound and reaches a squeaking sound when tightness is too high. Ten users have tested the moka and found the sound metaphor natural and the sonic feedback useful to perform the task.

The Drilling Machine Grosshauser et al. (Grosshauser and Hermann, 2010) developed a prototype to study the interaction loop between a human user and a tool in operation like a drilling machine. When a user interacts with a tool, the user combines different feedback from the eyes (visual), the skin (sensory), the nose (olfactory) and the ears (auditive). They proposed the creation of a nonexistent auditory feedback for a task such as like drilling, using a cordless electric screwdriver. The wanted to know how this feedback could be useful to add/support or replace the visual sense. The authors worked on the sonification with pulsing sounds to make audible if the drilling machine is horizontally and vertically in the right position, mostly a 90 deg. angle to the wall while drilling and screwing [6].

The Pebble Box O'modrhrain et al. (O'Modhrain and Essl, 2004; Essl and O'Modhrain, 2005; O'Modhrain and Essl, 2013) have worked on the integration between sound and touch through three different prototypes: the Pebble Box, the CrumbleBag and the Scrubber. The mapping between the sound feedback and the actions are related to some shared, physically informed relationship with its associated gestures or actions. They build an object that resembled to a musical instrument. The PebbleBox is constructed as a wooden box, which contains a layer of polished stones. When the users manipulate the stones, granular synthesis of natural sound recordings provide different collision sounds that change the relationship between action and sound but retaining the core physical dynamics of the original link. With the same principles, CrumbleBag focused on crumbling action and the Scrubber on friction actions. An interesting approach is to keep the core physical dynamics of the original link between action and sound but changing the sound properties to modify the experience.

The Gamelunch Authors developed an interactive installation based on everyday objects and actions, a sonic dining table called the Gamelunch (Polotti et al., 2008; Delle Monache et al., 2013). They worked on contradictory relationships between action and sound. The literature on sound event perception make distinction between the structural invariants of an event specify the type of object and its properties and the transformational invariants specify the changes occurring in the sound sources (Houix et al., 2012). For example, when pouring a liquid from a decanter, a solid friction sound gives the feeling of a resisting force that contradicted the feeling of the decanter becoming lighter as liquid was poured from it. Another example is focused on the action of stirring a soup, when the participant produced

[6] A demo S.5.4 is available at http://sonification.de/handbook/index.php/chapters/chapter5/

this action a sound of a tool mixing floating stones is provided, which was in contradiction with the visual image of the soup in the dish.

6.3.2 Sonic interaction design and evaluation

We present here experimental studies that tested the assumption that a gesture will be adjusted intuitively and spontaneously if its associated sound helps to draw an analogy with the action that caused it.

The Balancer Rath et al. (Rath and Rocchesso, 2005; Rath, 2007) has tested a similar hypothesis in a first experimental study with an interactive sound device. This interactive sound device used, the Balancer, corresponded to a very simple interface consisting of a wooden fence that participants could tilt. The manipulation of the interface controlled a synthesis model simulating a ball rolling along a guide. Using a model of virtual ball, users were informed of its position and velocity as a visual or audible feedback. They had to do things like, for example, bring the ball to a target area of the guide. A first "mapping" between sound and action is performed using a corresponding realistic sound of a ball rolling on wood by sound synthesis in real time based on a complex physical model, this corresponds to a "causal mapping". In a second step, the sound used was an abstract but retaining its features to have information about the position and velocity of the ball, this corresponds to an "abstract mapping". The results showed that both types of "mapping" enabled the control of the virtual ball. However, the "causal mapping" induce faster learning, this advantage disappears after a few tries. This study highlights the influence of the sound component on the performance of participants.

The spinotron This study by the PDS team was conducted in collaboration with the Graduate School of Design Zurich (ZHdK) (Lemaitre et al., 2009). An object has been created, the Spinotron, which consists of a vertical pump, see figures 5 and 6. Several mapping between sound and action were created and tested. The first one, based on the metaphor of a ball rolling in a bowl, itself rotated by the action of the user on the pump, was too complex to be used, the listeners did not understand the mapping to control the action. The second mapping was based on the metaphor of a top rack. The action of the pump rotates a virtual gear, which is synthesized by the clicking of a physical impact model. A first experiment, based on listening tests showed that listeners are able to perceive significantly the speed rotation of the wheel. The "mapping" is perceived. Then, in the context of use, we investigated whether the sound of the gear guide the handling of the device to perform a specific task. The task was to achieve a given rate by pressing the device with and without audio feedback. The influence of the feedback was examined by assessing learning in twelve successive tasks.

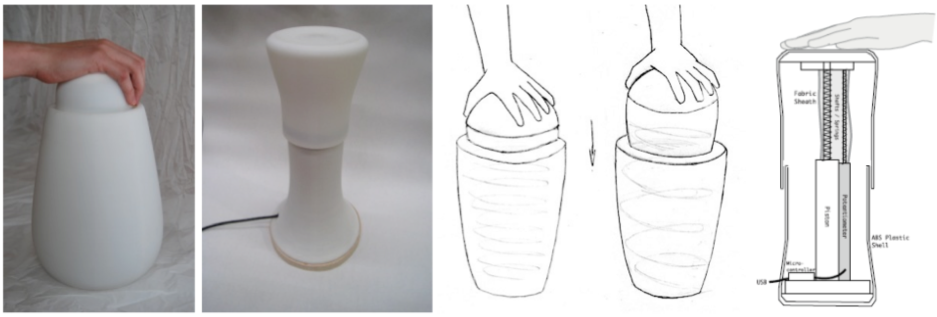

Figure 5: Left: the Spinotron affords vertical pumping and generates digitally synthesized sounds. Right: the configuration of the Spinotron device.

The results show that while participants have said they were not helped by the sound, the performance is significantly improved by the presence of sound. This result confirms a good "mapping" between the action and the associated sound.

These results highlight the influence of the sound dimension during an interactive process with a tangible object, and found that interactive features are a relevant field of exploration to develop knowledge about the processes combining perception and action in our daily sonic environment. Furthermore, the studies with the Spinotron as the study with the Balancer valid the interest to design devices incorporating a sound component.

The fl)o(ps An object has been created, the Flops, consisting of a glass that can pour virtual balls (Figure 7), with the same collaboration as the Spinotron (Lemaitre et al., 2012). The objective is to study the induced emotions (valence: calm-stimulating, arousal: pleasant-unpleasant and dominance) by the sound dimension when handling the device. The task of the participants is like a game: they have to dispense exactly ten virtual balls. Two different "mappings" between sound and action called "causal" and "abstract" are associated with the impact of the ball on a surface, and different levels of handling, more or less difficult, are controlled from the simulation model balls (speed and ball size, length of the glass). For the "causal mapping" real impact sounds are used. For the "abstract mapping" sounds were created covering different parameter values: pitch and spectral center of gravity - the latter parameter appearing as "universal" for describe different classes of sounds from everyday objects. The results show that, although, of course, the difficulty of handling the device has the greatest influence on emotions - associated with the success to achieve the given task but the more or less pleasant sounds also affect emotions, but with a small but significant effect. We have shown that the pleasantness character can be manipulated by altering the frequency content of the sound - more

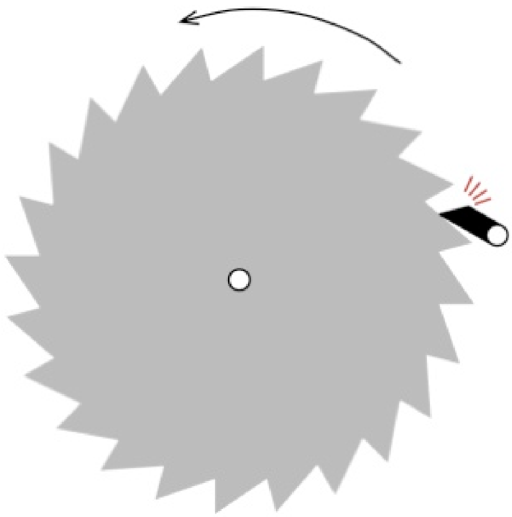

Figure 6: A sound synthesis model was designed based on a ratcheted wheel, whose rotation is driven by the pumping motion of the Spinotron.

negative emotions to a high value of spectral center of gravity - and the kind of "mapping" sound, a "causal mapping induces a more positive emotion. These results are useful indications for the sound designer who wants to work on the emotional relationship with an object a priori silent.

The ATM The question we ask here (Susini et al., 2012b) in a simpler way than the Spinotron or the Flops is the following: is a "causal" sound considered more functional and better accepted that an "abstract" or "arbitrary" sound? A "mapping" is "abstract" when the relationship between the action and the sound keep the dynamic of the acoustical properties contrary to a pure, arbitrary relationship. The three "mapping", respectively "causal" "abstract" and "arbitrary", were compared in a controlled interactive context corresponding to the use of a numeric keypad (ATM) to perform banking transactions (withdrawal and transfer between accounts). Sound was associated with the keys. Two levels of difficulty of the device were tested: "normal" and "abnormal". The originality of the experience lies in the fact that the auditors used the keyboard with the sound they had tried before. The results show that before using the keyboard, the sounds judged as the most "natural " (concerning the relation between to the action of pressing a key and the sound produced) are considered as the most functional. This judgment persists after using the keyboard. Sounds that are judged significantly more "natural" are more functional and pleasant in interactive context. This is the case for the "causal mapping". Arbitrary sounds are, for them, considered less functional and pleasant, and even less

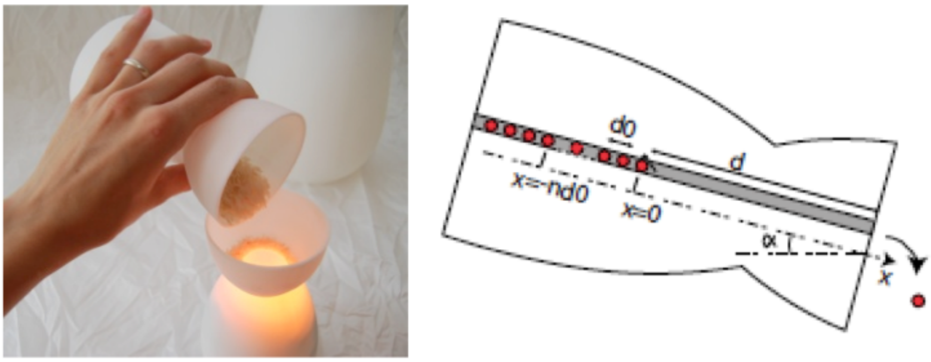

Figure 7: Left: A video showing a user using the Flops glass. Right: Model used for the interaction

after using the keyboard. In contrast, judgments obtained for the intermediate level ("abstract mapping") depend on the difficulty level of the device and are considered much more functional and pleasant after using the keyboard. However, for an abnormal difficulty of use, the abstract mapping is no longer considered as functional and pleasant.

6.4 Conclusions

Different studies we did not develop here (see (Susini, 2011) for a review) show that the hearing is better adapted to the perception of an action, and that the temporal dimension is an important factor to distinguish different classes of actions. The question of the meaning of a sound is fundamental when the sound dimension is involved during the interaction with an object. We presented studies and experimental devices in the context of sound design that addressed the function of sound in a way that extend the framework of human-machine interfaces, considering interactive devices.

The description of the causal level of sounds revealed two classes of temporal profiles associated respectively with two classes of actions held with an object: a continuous temporal profile that corresponds to a continuous action; and a discrete temporal profile that corresponds to a discrete action or a series of discrete actions. Different time profiles were considered in actions respectively to guide the manipulation of a device (the Spinotron, the Ballancer) or confirm an action (ATM) or a mix of the two classes (The Game lunch).

The different results and experimentations highlight the effect of the sound dimension to improve performance, enhance learning and give a positive reaction - pleasant - in an interactive handling with an object. However it depends on the acoustic characteristics and the type of sound - causal, abstract, arbitrary - at stake, but also the functional aspect of the device handled. In conclusion, the results showed that interaction will be more relevant when the associated sound will establish an analogy with the action that is the cause, and that this action is consistent with the possible manipulation of object.

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